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I. Scientific Research Goals

The goals of this research are

- Understand and clarify the physical mechanism underlying the electrorheological (ER) phenomenon, such as viscosity, the structure of ER fluids, phase transitions, and properties.
- Apply the ER phenomenon to fuels to control viscosity.
- Study cryogenic ER fluids and investigate applications of the ER effect to slurry rocket fuels.

II. Significant Results**1. Structure of ER Fluids.**

What is the structure of ER fluids in an electric field? This is important to understand ER fluids. It was found quite a while ago that in an electric field, ER fluids form thick columns spreading between two electrodes. The structure of these thick columns puzzled many authors in this field until our recent work which clarifies this issue.

We assume that the dielectric particles are balls with radius of a . Inside an electric field \vec{E} , each particle obtains a dipole moment $\vec{p} = \alpha \vec{E}$ where α is a constant. We take the direction of electric field as the z -direction, and define

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infinite chains with their dipoles at $z_j = 2ja$ ($j = 0, \pm 1, \pm 2, \dots$) as chains of class A and infinite chains with $z_j = (2j + 1)a$ as chains of class B. The columns are found to be formed by chains A and B only.

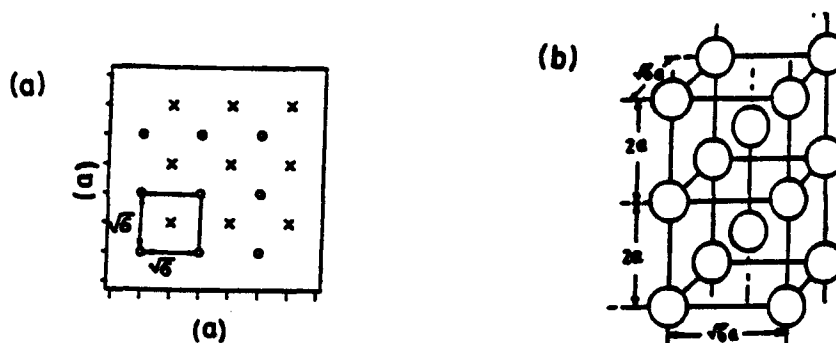


Fig.1. (a).The projection of the three-dimensional structure to the x-y plane where o for A chains and x for B chains. (b).Three-dimensional body centered tetragonal (bct) structure, the ground state of the induced ER solid (the particles have radius a and are not shown to the scale).

The interaction between two infinite chains are short-ranged. Two chains of the same class are repulsive, while two chains of different classes are attractive. Their interaction energies can be represented as

$$U_{AA}(\rho) = U_{BB}(\rho) = -U_{AB}(\rho) = \frac{\pi^2 p^2}{\epsilon_f} \sqrt{\frac{2}{a}} \frac{1}{a^3 \rho} e^{-\pi \rho/a}.$$

The distance between two chains of different classes is $\rho \geq \sqrt{3}a$, but the distance between two chains of the same class is $\rho \geq 2a$. The ground state is the configuration which minimizes the total potential energy. Therefore, the structure of ER fluids is equivalent to finding a ground state for a two-dimensional system which has two classes of particles A and B in $x - y$ plane via the above interactions. It is well known that this should be a square crystal as shown in Fig.1(a). Fig. 1(b) is the three-dimensional structure recovered from Fig.1(a): It is a body-centered tetragonal lattice [1]. In other words, Fig.1(a) is just the projection of Fig.1(b) to the x - y plane.

2. Monte Carlo simulation of ER fluids .

We have used Monte Carlo simulated annealing process to explore the ideal structure of ER fluids in an electric field [2]. The structure of ER fluids is the configuration which minimizes the potential energy. In our simulation, we first give a random distribution of dielectric particles in the space and calculate their interaction energy U_0 . Meanwhile, we introduce a temperature T . Then we try to move the particles randomly in space. After one trial move, we calculate the new energy U_i and find the difference $\delta U = U_i - U_0$. If $\delta U \leq 0$, the move is allowed, the new state replaces the initial state. If $\delta U > 0$, we do not reject the

new state immediately. The probability to move to the new state is $\exp(-\delta U/T)$. This slow process will avoid the possibility to lead our Monte Carlo process to a local minimum. We repeat the above process again and again. Meanwhile, the temperature T is gradually cooling down to 0. Our Monte Carlo simulation finds that the ground state of ER fluids is just the bct lattice in Fig. 1.

3. Determination of the induced ER structure by laser diffraction

The prediction of a bct lattice as a many-body ground state of ER fluids has been confirmed by our Monte Carlo simulations, which have also shown that this structure can be realized at room temperature [2]. However, experimental verification of the structure is always crucial. Since the electric field-induced solidification in ER fluids is a relatively fast phase transition, it would be interesting to see if a regular lattice can be formed in the process. Furthermore, most existing theoretical models and calculations of ER fluid properties assume particles in chains rather than columns. Therefore, an experimental determination of column structure would be highly significant for future research and applications.

We have used laser beam diffraction to investigate the structure of induced ER solid, which confirms the predicted bct lattice structure [3]. The diffraction mechanism, however, is totally unlike that of conventional X-ray scattering by crystals.

Our ER fluid consists of a low viscosity silicone oil containing size-selected glass micro-spheres of highly uniform diameter, either $20.0 \pm 1.8 \mu\text{m}$ or $40.7 \pm 1.7 \mu\text{m}$ (SPI Supplies, Westchester, PA). The glass spheres were pre-treated to develop an absorbed H_2O film which greatly enhances their effective dielectric constant, and then the spheres were mixed with oil to a volume fraction about 0.2. On a horizontal microscope glass slide we mounted two parallel brass electrodes which are 3 mm thick and separated by 3 mm. Then three glass spacers were used between the electrodes, one at the bottom, two at the two sides, to form an ER fluid cell in a region of most uniform electric field. Only a small drop of the ER liquid is needed to fill the cell, measuring 3 mm \times 3 mm horizontally and 0.3 mm in vertical depth. The top surface of the fluid is open (no cover glass is used). Before an electric field was applied, the spheres stayed at the bottom and formed several layers. We stirred the ER fluid in the cell first to make the spheres spread into the space, then we began to apply an electric field. The solidification process takes about 5 minutes and is recorded by a video camcorder, showing the formation of chains then columns for applied electric fields $\sim 1 \text{ KV/mm}$. If the field is maintained for several hours, the oil leaks out of the cell, the structures become "locked" in place, remaining fixed after removal of the field. The averaging column width is 0.6 mm. The column thickness vertical to the slide is about 0.15 mm. The average separation between two columns is generally several column widths.

The diffraction of a laser beam by glass spheres in a closed-packed lattice

such as that shown in Fig. 2(a) needs to be carefully examined. It certainly is not analogous to conventional X-ray diffraction by a crystal. For X-rays, a crystal is essentially transparent with a 3-dimensional array of small scattering centers (nuclei and electrons) that produce far-field interference patterns. In our ER structure, the glass spheres have a size much larger than the laser wavelength ($0.63 \mu\text{m}$), and the closely packed structure is "optically dense" in the sense that there are very few paths for light to travel without encountering a number of spheres. In fact, for example, there is no direct path in the $[110]$ direction. Although one might expect diffuse scattering of a laser beam due to multiple reflections and refractions by the spheres, a mechanism for producing regular patterns is not immediately obvious.

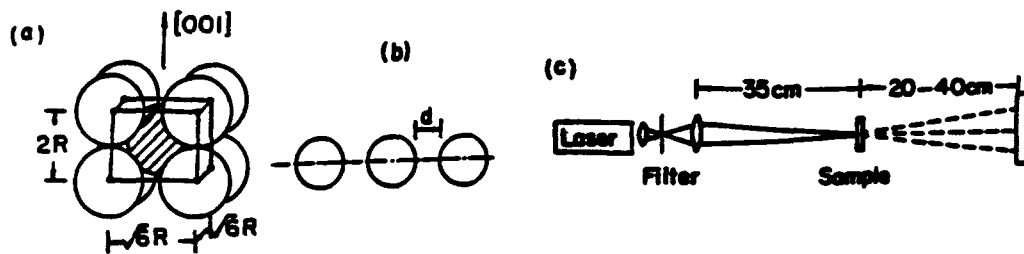


Fig.2. (a) Unit cell of our proposed bct lattice for spheres of radius R , where the $[001]$ axis is the applied field direction. (b) A linear periodic array of glass spheres of radius R separated by distance d . (c) Layout of the diffraction experiment. In the sample, whose view is given in Fig.2(a), the applied electric field direction $[001]$ is perpendicular to the optic axis.

We have proposed the following process. Since each glass sphere acts as a "thick" lens, a linear periodically spaced set of spheres, as shown in Fig.2(b), constitutes a periodic array of focussing elements. An analysis of such arrays can be found in many texts, where it is shown that light rays can propagate stably and indefinitely along an appropriately spaced set of such elements. In other words, there are stable ray modes that do not diverge from the axis, or leave the array. This analysis is often employed in laser design, where an infinite array is used to represent the end-reflectors of an optical cavity. Mathematically, the path of a ray along a single periodic length is characterized by a 2×2 matrix M , and stable ray modes exist if the absolute value of the trace of M is less than 2.

The calculation of M is simple for "paraxial" rays close to the array axis that make only small angles from the axis. For the array represented in Fig.2(b), the matrix for the period from the front surface of one sphere to the front surface of the next is given by

$$M = \begin{pmatrix} [(2-n)/n] + [2d(1-n)/nR] & [2R/n] + [d(2-n)/n] \\ 2(1-n)/nR & (2-n)/n \end{pmatrix}$$

where R is the radius, n is the ratio of the refractive index of the spheres to the refractive index of air medium, and the matrices in the product, reading from

right to left, represent respectively (i) refraction entering a sphere, (ii) traverse through the sphere, (iii) refraction leaving the sphere, and (iv) traverse of the space d between two spheres. Each of these matrices can be found in the ray-matrix tables. For stable ray modes, the absolute value of the trace of M must be less than 2. Then, we obtain the stability condition

$$d < 2R/(n - 1).$$

Our samples, after the oil leaks out, have $n = n_{\text{glass}}/n_{\text{air}} = 1.51$ and thus we require $d < 3.9R$ for stable mode propagation. For the bct lattice shown in Fig. 2(a), all directions $[m, n, l]$ with low indices ($m, n, l = 0, \pm 1$) satisfy the above condition, and accordingly, stable paraxial ray modes may propagate along these directions. More extensive calculations show that stable non-paraxial modes may also propagate in the bct lattice.

Thus, stable modes travel along each linear array and emerge from the final sphere to a focus beyond the last lattice plane. The focal waist size is only a few micrometers in diameter, small in comparison with the sphere radius. The set of such focal "points" is essentially a 2-dimensional array (not 3-dimensional as in X-rays) that produces a diffraction pattern. The form of the far-field diffraction pattern is just the reciprocal lattice of the exit plane.

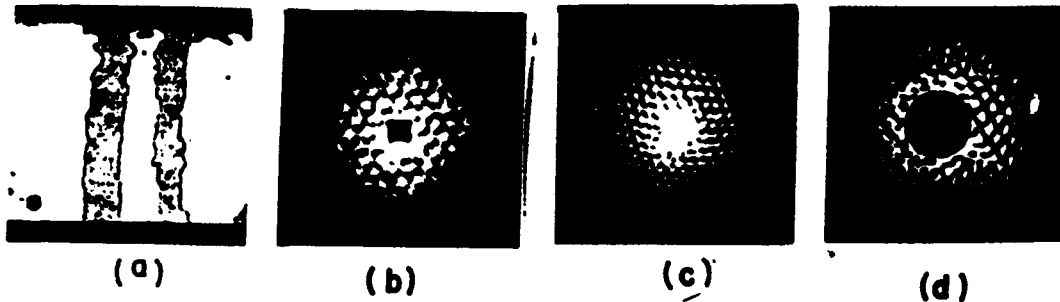


Fig.3. (a) View of typical columns formed between the two electrodes which are separated by 3mm. (b) Diffraction pattern of a (110) plane for 20.0 μm diameter spheres. (c) Pattern of a (110) plane for 40.7 μm diameter spheres. (d) Pattern of a (100) plane for 40.7 μm diameter spheres. In (b) and (d), the centers are masked to suppress overexposure.

The experimental optical diffraction arrangement is shown in Fig.2(c). A 5mw He-Ne laser beam is passed through a spatial pinhole filter to obtain a clean Gaussian intensity profile and then is focused onto an individual column of the sample. The focused laser beam has a Gaussian diameter about 0.1 mm or 1/6 of the average column width. The sample is on a micrometer adjustable mount for translation and angular rotation. We note a fundamental difference between our experiment and conventional X-ray diffraction by a crystal. In the latter case, the Bragg condition requires a specific orientation of the incident beam relative to crystal planes, and all orientations must be used to obtain a complete pattern. By contrast, our experiment is insensitive to the incident beam direction and an

entire planar pattern for the lattice exit plane is obtained for a single orientation of the sample relative to the incident beam. This is because each sphere in the first layer encountered by the beam produces refracted rays in various directions, from which propagating array modes are selected by deeper-lying layers.

The bct lattice structure can be identified by the structures of the (110) and (100) planes. The (100) plane has a rectangle $\sqrt{6}R \times 2R$ as a primitive cell, while the (110) plane is a centered rectangular lattice of $2\sqrt{3}R \times 2R$. Fig.3(a) is a microscopic view of typical columns. Fig.3(b) shows a diffraction pattern produced by a sample with $20.0 \mu\text{m}$ diameter spheres. The geometry of this pattern is precisely the reciprocal lattice of the (110) plane in the bct structure and the structure constants derived from the pattern are precisely those expected for this plane. This implies that the transmission axis of stable ray modes is along axis [110]. Fig.3(c) shows a pattern from a sample with $40.7 \mu\text{m}$ diameter spheres. Here the pattern is also that of a reciprocal lattice of the (110) plane, but twice as dense as in Fig.3(b) because with spheres twice as large the reciprocal spacing is smaller by $1/2$. In Fig.3(d), the sphere diameter is $40.7 \mu\text{m}$ and the pattern is obviously more rectangular than the preceding cases; it is in fact, precisely the pattern expected for a (100) plane. In this case, the transmission axis of stable ray modes is [100]. The direction [010] is equivalent to [100] in the bct structure. All of our samples have shown the diffraction patterns consistent with the bct lattice structure.

Table I lists experimental results of the structure constants compared with theoretical values for the bct lattice. In all cases, there is agreement to within a few percent. As mentioned earlier, the diameters of our spheres are known to be non-uniform to this degree. Accordingly, the data are entirely consistent with the proposed bct lattice.

Table I. Structure constants

Lattice Plane	Sphere Diameter	Experiment	Theory
(110)	$20.0 \mu\text{m}$	$a = 34.1 \mu\text{m}$	$34.6 \mu\text{m}$
		$b = 21.1 \mu\text{m}$	$20.0 \mu\text{m}$
(110)	$40.7 \mu\text{m}$	$a = 69.1 \mu\text{m}$	$70.5 \mu\text{m}$
		$b = 38.9 \mu\text{m}$	$40.7 \mu\text{m}$
(100)	$40.7 \mu\text{m}$	$a = 54.8 \mu\text{m}$	$49.8 \mu\text{m}$
		$b = 43.8 \mu\text{m}$	$40.7 \mu\text{m}$

4. Order parameters and phase transitions in ER fluids

From the theory of critical phenomenon, it is well known that the order

parameters are the key quantities to specify the many-body system in the study of phase transition. The ground state of an induced ER solid is the bct lattice in Fig.1 (a). The reciprocal lattice vectors are $\vec{b}_1 = 2\pi\hat{x}/\sqrt{6}R - \pi\hat{z}/R$, $\vec{b}_2 = 2\pi\hat{y}/\sqrt{6}R - \pi\hat{z}/R$, and $\vec{b}_3 = 2\pi\hat{z}/R$. Three order parameters are, therefore, defined as $\rho_j = \sum_{i=1}^N \exp(i\vec{b}_j \cdot \vec{r}_i)/N$, ($j = 1, 2, 3$), where N is the total number of particles. Among them, ρ_3 characterizes the formation of chains in the z direction, while ρ_1 and ρ_2 characterize the structure in the x - y plane.

We introduce a dimensionless quantity $\theta = kTd^3\epsilon_f/(\bar{p})^2$ which characterizes the ratio between the thermal energy and the dipolar interaction energy [4,5]. To calculate $\bar{\rho}_j$, we apply the Metropolis algorithm. Our simulations take $N = 178$ dielectric particles inside a capacitor with spacing $L = 28a$. In the x and y directions, the system has $360a \times 360a$ and a periodic boundary condition. We start at $\theta = 0$, then increase θ slowly. The state of $\theta = 0$ represents extremely strong electric field which has the ideal bct lattice structure. For each θ , the simulations repeat $1000N = 178000$ Monte Carlo steps. In each step, we pick a particle in the configuration to make a trial move to a position randomly distributed in the space, then calculate the change of dipolar interaction of the system due to the random move, δU_d . If $\delta U_d \leq 0$, we accept the new configuration. If $\delta U_d > 0$, the probability to accept the new configuration is $\exp(-\delta U_d/kT)$. When the new configuration is accepted, we calculate the new ρ_j ($j = 1, 2, 3$) for statistical average. If the new configuration is rejected, the previous configuration is retained and the previous values of ρ_j are counted again in statistical average. Then, the next random trial will be either on the newly accepted configuration or the retained previous configuration. After $1000N$ Monte Carlo steps are completed for one θ , we calculate the average values of ρ_j . Then, we increase θ by 0.01 and repeat the above procedure. The starting configuration at $\theta + 0.01$ is the final configuration at θ . To make sure that our average obtained on the Metropolis sampling is the true canonical ensemble average, we examine the results after $200N$, $400N$, $600N$, $800N$, and $1000N$ Monte Carlo steps and see how they are stabilized. This examination convinces us that the Metropolis sampling is effective.

The absolute values of $\bar{\rho}_j$ are plotted in Fig.4. It is clear that $|\bar{\rho}_1|$ and $|\bar{\rho}_2|$ have almost identical behavior, while $|\bar{\rho}_3|$ is noticeably different. At $\theta = 0$, all the three order parameters equal to unity. As θ increases, $|\bar{\rho}_j|$ ($j=1,2,3$) remains unity for a while. Then, near $\theta = 0.16$, $|\bar{\rho}_1|$ and $|\bar{\rho}_2|$ drop quickly, while $|\bar{\rho}_3|$ does not drop quickly until θ reaches 0.22. Afterwards, $|\bar{\rho}_1|$ and $|\bar{\rho}_2|$ tend to zero much faster than $|\bar{\rho}_3|$. There are two important quantities, $\theta_1 = 0.28$ and $\theta_2 = 0.67$. When θ reaches θ_1 , $|\bar{\rho}_1|$ and $|\bar{\rho}_2|$ are essentially vanishing and their fluctuation after $\theta > \theta_1$ is due to the finite size effect. However, $|\bar{\rho}_3|$ does not vanish until θ reaches θ_2 .

The above results indicate three regions of θ [4]. For $0 \leq \theta < \theta_1$, all three

$|\bar{\rho}_j|$ are non-vanishing; the ER system is a solid whose ideal structure is the bct lattice. When $\theta_1 < \theta < \theta_2$, $|\bar{\rho}_1| = |\bar{\rho}_2| = 0$ while $|\bar{\rho}_3| > 0$. Since ρ_3 characterizes the formation of chains in the z direction, the ER system in this state has chains in the field direction, but the distribution of these chains is random, no ordering in the x and y directions. It is clear that this state is similar to an induced nematic liquid crystal, because the chains have orientation in the z direction. As $\theta > \theta_2$, $\bar{\rho}_1 = \bar{\rho}_2 = \bar{\rho}_3 = 0$, the ER system is a fluid with no ordering at all.

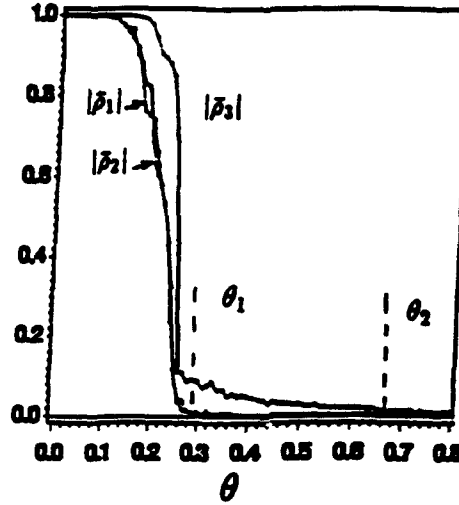


Fig.4. Change of $|\bar{\rho}_1|$, $|\bar{\rho}_2|$, and $|\bar{\rho}_3|$ vs θ . The curves of $|\bar{\rho}_1|$ and $|\bar{\rho}_2|$ are almost identical, while $|\bar{\rho}_3|$ decreases much slower than $|\bar{\rho}_1|$ and $|\bar{\rho}_2|$ as θ increases.

The canonical ensemble average of the dipolar interaction per particle, \bar{U}_d/N , is plotted in Fig.5. Though our system is small, \bar{U}_d/N clearly shows a jump as θ crosses θ_1 , indicating the first order phase transition from the nematic liquid crystal state to the solid state. Since \bar{U}_d/N is smooth at θ_2 with no jump, the phase transition from the fluid state to the liquid crystal state is of the second order. At $\theta = 0$, $\bar{U}_d/N = -2.71188p^2/(\epsilon_f d^3)$ which is slightly higher than $-3.050144p^2/(\epsilon_f d^3)$, the value for the infinite bct lattice. This deviation is due to the finite size effect, since a system of 178 particles plus their images is a finite bct lattice with defects and surfaces. We also note that a face-centered cubic lattice of the same small size has dipolar energy $-2.65465p^2/(\epsilon_f d^3)$ per particle, still higher than that of the bct lattice [5].

Let us estimate the latent heat for the first order phase transition. We define a parameter $\eta = -2\bar{U}_d d^3 \epsilon_f / (N p^2)$. Then the average dipole field is given by $\Delta \vec{E} = \eta \vec{p} / (\epsilon_f d^3)$. Our results indicate that the dipole field and hence η is sensitive to the distribution of dielectric particles. Using the Lorentz's self-consistent method, we have the average $\vec{E}_l = \vec{E} / (1 - \alpha \eta / 8)$, the quantity $\nu = p^2 / \epsilon_f = \alpha^2 a^3 E^2 \epsilon_f / (1 - \alpha \eta / 8)^2$, and the average Coulomb energy per particle $\bar{U} / N = -\frac{1}{2} \alpha a^3 \epsilon_f E^2 / (1 - \alpha \eta / 8)^2$. If η decreases from η'_1 to η_1 when θ passes θ_1 , the latent heat per unit

volume is given by

$$3\phi\alpha\epsilon_f E^2 [(1 - \alpha\eta'_1/8)^{-2} - (1 - \alpha\eta_1/8)^{-2}] / (8\pi)$$

where $\phi = 4\pi a^3 n/3$ is the volume fraction of the particles in the system. This latent heat is very small for a typical ER fluid. As a rough estimation, we take $\eta_1 \approx 0$ and $\eta'_1 \approx 6$, $\phi = 0.4$, $E = 10$ KV/cm, $\epsilon_f = 2.2$ (for petroleum oil), $\alpha = 0.5$, the latent heat is only about 180 erg/cm³.

We can consider to induce the phase transitions in the ER fluid by two different approaches: (1) At a fixed temperature, increase the applied electric field; (2) at a constant applied electric field, lower the temperature of the ER system. When the ER fluid has a fixed temperature, two critical electric fields are given by

$$E_{ci} = (1 - \alpha\eta_i/8) \sqrt{8kT/(\alpha^2\epsilon_f a^3 \theta_i)}, \quad (i = 1, 2),$$

where η_2 is the value of η at θ_2 . When $E < E_{c2}$, the ER system is in a liquid state. As $E_{c2} < E < E_{c1}$, the ER system is similar to the induced nematic liquid crystal. As $E_{c1} < E$, the ER system is in the solid state.

When the ER fluid is under a constant electric field, we have two critical temperatures,

$$T_{ci} = \alpha^2 \epsilon_f a^3 E^2 \theta_i (1 - \alpha\eta_i/8)^{-2} / (8k), \quad (i = 1, 2),$$

if ϵ_f and ϵ_p have little change in the temperature range under our consideration. When $T > T_{c2}$, the ER system is a liquid. When $T_{c2} > T > T_{c1}$, the ER system is similar to nematic crystal state. When $T < T_{c1}$, the ER system is the solid bct lattice.

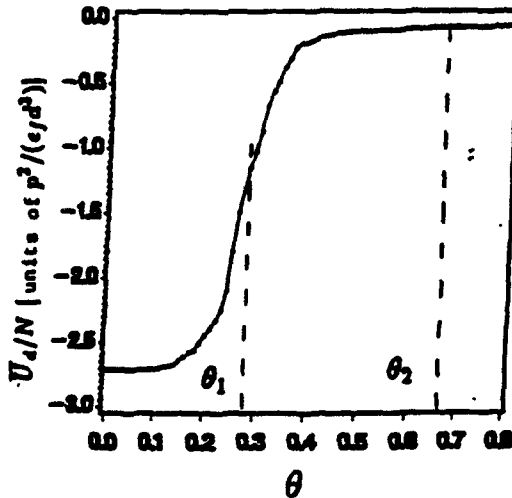


Fig.5. Change of \bar{U}_d/N vs θ . When θ crosses θ_1 , \bar{U}_d/N has a jump. There is no jump at θ_2 .

5. Organizing an International Conference on ER fluids

With the support from ONR and Southern Illinois University at Carbondale (SIUC), we organized an International Conference on ER Fluids on October 15-16, 1991 at SIUC [6,7].

The meeting was organized to bring together the experts in this field to explore the state-of-art of this technology, and to disseminate the most recent research developments. Technical sessions included Materials Technology, Physical Mechanisms, Properties, and Applications, together with a poster session. The response from the scientific and engineering community was overwhelmingly positive. The meeting provided a forum for collaboration and interaction of industry and academia, which is required for the success of any emerging technology. Participation from UK, Japan, USSR, China, Germany, France and USA is evidences of the truly international interest in this technology area. It is evident from the presentations that considerable advances have been made in understanding the physics of ER fluids, and that the technology is applied in several components.

The Electrorheological Conference has provided one step to achieve the goal of understanding, controlling and applying ER phenomena.

6. Cryogenic ER Fluids and Rocket Fuels.

An important case of a highly energetic fuel is a slurry fuel made of aluminum powder in liquid oxygen. An immediate question is whether this mixture can act as an ER fluid. Although aluminum is a conductor, its particles naturally form an insulating oxide coating so that an applied electric field is not short-circuited, while the metal itself has an extremely large dielectric constant. Liquid oxygen has a very low dielectric constant, and that difference in dielectric constant should produce a strong ER effect. Rapid, precise computer-controlled flow without mechanic moving parts is particularly attractive for cryogenic applications. Another intriguing possibility is that with the reversible ER phase transition in an electric field, slurry fuels can be stored and transported as solid fuels and combusted as liquid fuels.

We have carried out experiments on cryogenic slurries, with nitrogen substituted for oxygen to avoid problems of accidental combustion in the laboratory [8]. Since liquid nitrogen and liquid oxygen have comparable dielectric constant, density and boiling point, the substitution should not influence the validity of the results. Slurries were produced with aluminum powder of diameters $\sim 10 \mu\text{m}$ at a volume concentration $\sim 20\%$. An electric field was applied between two electrodes $21 \times 8 \text{ mm}^2$ separated by 3 mm. A semi-quantitative estimate of the strength of the ER effect was obtained from the value of field required to keep material between the electrodes from falling under gravity when the electrodes were lifted from the bath.

The slurries indeed acted as ER fluids. The effects of dc and 60 Hz ac fields

were compared and the ac fields were significantly more effective. We believe that the reason lies in the fact that the aluminum particles have a small but non-zero conductivity σ although they have an oxide coating. Since the dielectric constant $\epsilon(\omega) = \epsilon_0 + i\sigma/\omega$ (SI units), we need an ac field $\omega > \sigma$ to suppress the weakening effect of the conductance on the induced dipole moment. Fields above 10 kV/cm produced the thick chains and columns of particles between the two electrodes that are characteristic of strong ER fluids. When the field was reduced, column structure persisted until the field reached 3 kV/cm, below which the columns finally dispersed. The reason for the hysteresis is under investigation.

For a more quantitative study, we used a modified commercial rheometer to measure the effective viscosity of the suspension. When there is no field, there is a negligible viscosity. At a dc field of 1 kV/cm, the viscosity is about 155 cp. A further increase of the dc field gives little change of the viscosity. The results for ac field are shown in Table II. Overall, the viscosity for ac field is significantly larger than that for dc field, but it increases with the field E much less than the expected E^2 . This may very well be due to contamination of the ER fluid by particles of H_2O and CO_2 frozen from the surrounding air. We are presently constructing a "dry" box so that the experiments can be repeated in a nitrogen atmosphere.

Significant ER effects were also observed for suspensions of boron powder in liquid nitrogen. Future experiments on these and other systems will be carried out in quantitative detail, but the results to date are encouraging for the cryogenic fuel applications mentioned earlier.

Table II. Viscosity of a Cryogenic ER Fluid

Freq.	3kv/cm	3.75kv/cm	4.5kv/cm	5.25kv/cm
100Hz	208cp	253cp	278cp	290cp
500Hz	170cp	252cp	258cp	304cp
1000Hz	256cp	273cp	326cp	433cp

7. ER fuel valves.

According to current knowledge, a typical fuel with a suspension of dielectric particles should exhibit ER effects. We found that a dilute suspension of silica gel particles in a light petroleum produced an ER fluid that was readily flow-controlled and by electric fields [9]. For a horizontal flow tube 55 mm long of cross-section $6 \times 6 \text{ mm}^2$ with brass electrodes, the flow rate as a function of

electric field is shown in Fig.6. With increasing field, the flow rate decreases smoothly to cut-off (zero flow). The magnitude of the required field conforms to expectations based on the dielectric constants of the silica gel and the petroleum, as for other ER fluids.

These results confirmed the supposition that fuels could function as ER fluids, with properties that could be calculated from the electrical properties of constituents. Therefore, energetic (flammable) particles can be substituted for silica gel, the strength of the ER effect in the fuel will be determined primarily by the general factors involved in all ER fluids, and valve construction can follow the configurations that have already been shown to be efficient in ER flow control.

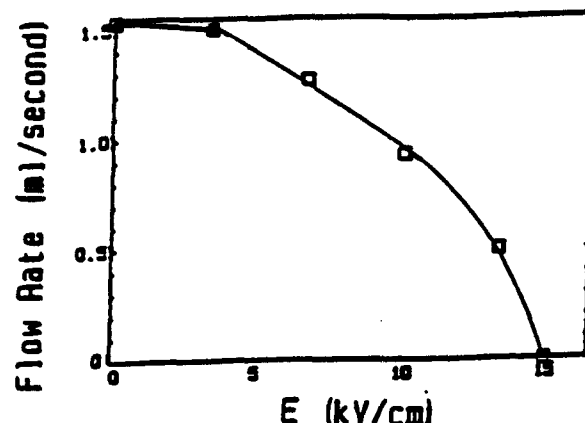


Fig.6 Flow rate as a function of electric field for silica gel particles in light petroleum.

8. Chain Deformation Under Fluid Flow.

The significant properties of ER fluids are determined by the internal strength of the structures. Therefore, it is important to understand and to be able to quantitatively describe the internal forces. The simplest structure to study is a single chain, which forms when an extremely dilute particle suspension is used. For an experimental measure of the internal force, we observed the deformation of a chain produced by steady fluid flow. The observed shape was in reasonable agreement with that calculated from a simple model of nearest-neighbor induced-point-dipole interactions for the internal chain force [10]. As a result of this study, we feel that induced point dipole interactions can be used to calculate the strength of ER structures if proper local field corrections are applied and if image forces by the electrodes are included.

9. Falling ball experiments in dilute ER fluids.

A well-known classic technique for determining the viscosity of a simple fluid involves a measurement of the terminal velocity of a ball falling through the fluid. Because of its simplicity, we adapted the technique to study the viscosity of a dilute ER fluid (silicon gel in vacuum pump oil), specifically to investigate the effects of particle size and particle concentration on the ER properties. Unlike a

simple fluid, an ER fluid exerts two retarding forces on the falling ball: a velocity-dependent Stokes-like viscous drag, and a velocity-independent force representing the work required to break field-induced chain structures. With a falling glass ball interrupting two laser beams along the path, velocity as a function of electric field was obtained for a variety of particle sizes and concentrations. The data, consistent in all cases with the model employed for analysis, show that the effective viscosity η depends on electric field E as $\eta = \eta_0(1 + \alpha E^2)$, where α is directly proportional to both particle diameter and volume concentration. The term αE^2 represents transient on impulse force on the chains. The chain-breaking force (which is directly related to the fluid's yield stress) depends on the field as βE^2 , where β is independent of particle size but varies with particle concentration as $c - c_0$, where c_0 is the minimum concentration for effective structure formation [11]. These results are in accord with less extensive measurements of yield stress made by others with a different technique.

10. Molecular dynamic simulations of solid structure formation in ER fluids.

We model an ER fluid as a mono-disperse suspension of spherical dielectric particles of dielectric constant ϵ_p in a nonconducting liquid with dielectric constant ϵ_f and viscosity η . The fluid is confined between two parallel electrodes. When there is no electric field present, the particles are randomly distributed. An applied electric field induces Coulomb interactions between the particles. In two-dimensional computer simulations, the particles likely form separated single chains if the thermal fluctuations are ignored. However, if the thermal fluctuations are included in the simulations, a triangular lattice (the only close-packed structure in two dimensions) is found to be the ER structure. When the thermal fluctuations are included in three-dimensional simulations, the electric field first forces the dielectric particles to form chains between two electrodes. Then the chains aggregate to form thick columns. The chain formation is fast, while the column-formation is relatively slow. We apply the order parameters to analyze the thick columns and find that they have a body-centered tetragonal (bct) lattice structure. These simulations conclude that the bct lattice is the structure of induced ER solid [12,13]

11. Static Shear Stress of ER Fluids.

We have calculated the static shear stress of an induced electrorheological (ER) solid for a single-chain structure, double-chain structure, triple-chain structure, and bct lattice [14]. When the shear strain is small, these three structures prefer slanted configurations which will come back to the original configurations if the load is removed. As the shear strain exceeds a yield point, the structures break into parts which cannot return to the original configurations in a short time. The bct lattice is found to have the strongest shear modulus. The triple-chain structure is weaker than the bct lattice, but stronger than the other structures.

The double-chain structure is weaker than the bct lattice, but stronger than the single-chain structure. The single-chain structure has the Peierls-Landau instability if the chain is very long. A double chain is stronger than a single chain if the chains are quite long and the situation is reversed if the chains are short.

III. Discussions

The field of ER fluids has come a long way since Winslow's seminal experiments with mixtures of corn starch and mineral oil in 1947 [15]. The pace of innovation has been particularly rapid in the last five or six years. Both US Department of Energy and the Government of Japan just released reports, assessing great potential of ER fluids for future industrial and technological applications. The thrust areas in which research is needed were also identified.

It can be seen from this report that our research on this ONR grant has made very important contributions to the field of ER fluids. This is also evidenced by the fact that one of the most influence journals, *Nature*, published a special report in news to explain importance of our research results [16]. *Scientific American* also reported our contributions as an important and significant discovery [17].

In this project, we also combined the basic research and application research together and balanced them. Our original idea to apply the ER effect to liquid fuels has now been proved to be correct. The results about ER liquid fuel valves indicate that these valves will have great potential in industries. We have also shown that the fast reversible electric-field induced phase transition can be used to convert slurry rocket fuels into solid fuels for storage and transportation and return them to liquid state at combustion. The ER effect may also be employed in control of combustion process of slurry fuels.

The present status of ER fluids can be summarizes as follows: the future is bright, while research and improvements are urgently needed.

We will continue our work on ER fluids and continue to make our contributions to the field.

IV. References

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3. T. J. Chen, R. N. Zitter, and R. Tao, Phys. Rev. Lett. **68**, pp 2555-2558 (1992).
4. R. Tao, International J. of Modern Physics B, **6**, pp 2635-2649 (1992).
5. R. Tao, Phys. Rev. E **47**, pp 423-426 (1993).
6. R. Tao, Materials & Processing, **7**, pp 5-7 (1992).
7. *Electrorheological Fluids*, (Proceedings of the Third International Conference on ER Fluids, Oct. 15-16, 1991 at Southern Illinois University, Carbondale, Illinois), edited by R. Tao (World Scientific Publishing, Singapore, 1992).
8. R. N. Zitter, X. Zhang, T. J. Chen, and R. Tao, "Cryogenic Electrorheological Fluids," in *Proceedings of the Fourth International Conference on Electrorheological Fluids* (World Scientific Publishing, Singapore) (in press).
9. R. N. Zitter, T. J. Chen, X. Zhang, and R. Tao, "Fluid Flow and Falling Ball Experiments in ER Fluids," in *Proceedings of the Fourth International Conference on Electrorheological Fluids* (World Scientific Publishing, Singapore) (in press).
10. T. J. Chen, X. Zhang, R. N. Zitter, and R. Tao, J. of Appl. Phys. **74**(2), pp 942-944 (1993).
11. R. N. Zitter, X. Zhang, T. J. Chen, and R. Tao, "Falling Ball Experiment in a Dilute Electrorheological Fluids," J. Appl. Phys. (Jan. 1994 issue).
12. R. Tao and Q. Jiang, "Simulation of Solid Structure Formation in an Electrorheological Fluid," in *Proceedings of the Fourth International Conference on Electrorheological Fluids* (World Scientific Publishing, Singapore) (in press).
13. R. Tao and Q. Jiang, "Simulation of structure formation in an electrorheological fluid" (submitted).
14. G. L. Gulley and R. Tao, Phys. Rev. E **48**, pp 2744-2751 (1993).
15. W. M. Winslow, J. Appl. Phys. **20**, 1137 (1949); U.S. Patent 2, 417, 850 (1947).
16. M. Whittle and W. A. Bullough, Nature, **358**, 373 (1992).
17. T. C. Halsey and J. E. Martin, Scientific American, **269**, N.4, 58, (1993).

V. List of Publications supported by the Grant

A. Papers in Referred Journals:

1. R. Tao, "Critical Volume in diffusion through random media," *Phys. Rev. A* **42**, pp 994-996 (1990).
2. M. A. Novotny, R. Tao, and D. P. Landau, "Relaxation in DLA with surface tension" *J. Phys. A* **23**, 3271-3278 (1990).
3. S. F. Wahid and N. K. Jaggi, "Harmonic Generation in $TlBa_2Ca_3Cu_4O_x$ Superconductor", *Physica (C)*, **V.170**, pp 395-404 (1990).
4. R. Tao, A. Widom, T. D. Clark, R. Prance, and H. Prance, "Theory of voltage biased Josephson pendulum", *J. of Physics: Condensed Matter*, **V.3**, pp 3505-3509 (1991).
5. N. K. Jaggi, "Structure and Dynamics of Dense Dipolar Fluids in an Electric Field and Their Relevance to Electro-Rheological Fluids " *J. of Statistical Physics*, **V. 64**, pp 1093 -1102 (1991).
6. R. Tao, "Path-integral approach to diffusion through random media", *Physical Review A*, **V.43**, pp 5284-5288 (1991).
7. R. Tao and J. M. Sun, "Three-dimensional Structure of Induced Electrorheological Solid," *Phys. Rev. Lett.* **67**, pp 398-401 (1991).
8. R. Tao and J. M. Sun, "Ground state of electrorheological fluids from Monte Carlo simulations," *Phys. Rev. A*, **44**, pp R6181-R6184 (1991).
9. R. Tao, "International Conference on Electrorheological Fluids," *Materials & Processing*, **7**, pp 5-7 (1992).
10. T. J. Chen, R. N. Zitter, and R. Tao, "Laser Diffraction Determination of the Crystalline Structure of an Electrorheological Fluid," *Phys. Rev. Lett.* **68**, pp 2555-2558 (1992).
11. R. Tao, "Order Parameters and Phase Transition in Electrorheological Fluids," *International J. of Modern Physics B*, **6**, pp 2635-2649 (1992).
12. R. Tao, "Electric-field induced phase transitions in electrorheological fluids," *Phys. Rev. E* **47**, pp 423-426 (1993).
13. T. J. Chen, X. Zhang, R. N. Zitter, and R. Tao, "Deformation of an Electrorheological Chain under Flow," *J. of Appl. Phys.* **74**(2), pp 942-944 (1993).
14. G. L. Gulley and R. Tao, "Static Shear Stress of Electrorheological Fluids," *Phys. Rev. E* **48**, pp 2744-2751 (1993).
15. R. N. Zitter, X. Zhang, T. J. Chen, and R. Tao, "Falling Ball Experiment in a Dilute Electrorheological Fluids," *J. Appl. Phys.* (Jan. 1994 issue).

16. R. Tao, "Fourth International Conference on Electrorheological Fluids," *Materials Technology*, Nov. 1993.
17. R. Tao and Q. Jiang, "Simulation of structure formation in an electrorheological fluid," (submitted).

B. Books (and sections thereof) Published:

1. *Electrorheological Fluids* (Proceedings of the Third International Conference on ER Fluids, Oct. 15-16, 1991 at Southern Illinois University, Carbondale, Illinois) published by World Scientific Publishing, Singapore, 1992.
2. *Electrorheological Fluids* (Proceedings of the Fourth International Conference on ER Fluids, July 20 - 23, 1993 Feldkirch, Austria), published by World Scientific Publishing, Singapore (in press).
3. N. K. Jaggi, J. T. Woestman, and R. Tao, "Possible Phase Transition in Electrorheological Fluids," in a book *Electrorheological Fluids*, pp 53-62 (edited by Carlson, Sprecher, and Conrad, Technomic Pub. 1990).
4. R. Tao and N. K. Jaggi, "Liquid fuel and electro-rheology fluids," in the Proceedings of the 3rd ONR Propulsion Meeting, (Newport RI, Oct. 15-18, 1990) pp 611-622.
5. R. Tao, "Symmetry breaking and fractional quantization of quantum systems", in *Symmetries in Sciences V*, pp 519-525 (edited by Bruno Gruber, L. C. Biedenharm, and H. D. Doebner, Plenum Press, New York, 1991).
6. R. Tao, "Electric field induced solidification — theory of electro-rheology fluids," in *Condensed Matter Theories, V 6*, pp 155-160 (Edited by S. Fantoni and S. Rosati, Plenum, 1991).
7. T. J. Chen, R. N. Zitter, and R. Tao, "Crystalline Structure of an Electrorheological Fluid Determined by Laser Diffraction," in *Electrorheological Fluids*, (World Scientific Publishing, Singapore, 1992) pp 15-20.
8. R. Tao, "Order Parameters and Phase Transition in Electrorheological Fluids," in *Electrorheological Fluids* (World Scientific Publishing, Singapore, 1992) pp 1-14.
9. R. Tao, "Phase Transitions and Order Parameter in Electrorheological Fluids," in *Proceedings of 2nd Minsk Heat and Mass Transfer Forum, VI*, pp144-150 (1992).
10. R. Tao, "Phase Transition and Structure of Electrorheological Fluids," in *Electrorheological Flows - 1993*, edited by D. A. Siginer, J. H. Kim, and R. A. Bajura (American Society of Mechanical Engineers, New York, 1993), pp 11-19.
11. R. N. Zitter, X. Zhang, T. J. Chen, and R. Tao, "Cryogenic Electrorheological Fluids," in *Proceedings of the Fourth International Conference on Electrorheological Fluids* (World Scientific Publishing, Singapore) (in press).

12. R. Tao and Q. Jiang, "Simulation of Solid Structure Formation in an Electrorheological Fluid," in *Proceedings of the Fourth International Conference on Electrorheological Fluids* (World Scientific Publishing, Singapore) (in press).
13. R. N. Zitter, T. J. Chen, X. Zhang, and R. Tao, "Fluid Flow and Falling Ball Experiments in ER Fluids," in *Proceedings of the Fourth International Conference on Electrorheological Fluids* (World Scientific Publishing, Singapore) (in press).
14. G. L. Gulley and R. Tao, "Static Rheological Properties of Electrorheological Fluids," in *Proceedings of the Fourth International Conference on Electrorheological Fluids* (World Scientific Publishing, Singapore) (in press).

C. Invited Presentations at Conferences:

1. R. Tao, "Electric Field Induced Solidification — Electro-Rheology Fluids", invited talk at Research Workshop in Condensed Matter, Atomic and Molecular Physics, International Physics Center, Trieste, Italy, July 18, 1990.
2. R. Tao, "Symmetry breaking and fractional quantization of quantum systems", invited talk at Symposium "Symmetry in Science V", Breganz-Lochu, Austria, August 3, 1990.
3. N. K. Jaggi, "Dynamics of Dense Dipolar Fluids in an Electric Field," Meeting of Rheology Society, Santa Fe, New Mexico, Oct. 22-25, 1990.
4. R. Tao, "Order Parameters and Phase Transition in ER Fluids", invited talk at the International Conference on ER Fluids, held on October 15-16, 1991, at Southern Illinois University at Carbondale.
5. T. Chen, R. N. Zitter, and R. Tao, "Crystalline Structure of an Electrorheological Fluid Determined by Laser Diffraction", invited talk at the International Conference on ER Fluids, held on October 15-16, 1991, at Southern Illinois University at Carbondale.
6. R. Tao, "Ground State of Electrorheological (ER) Fluids", invited talk at the American Physical Society 1992 March Meeting, 16-20 March 1992, Indianapolis, Indiana. The abstract is published in *Bulletin of the American Physical Society*, V.37, N.1, p570 (1992).
7. R. Tao, "Phase Transition and Order parameters in ER Fluids", invited talk at the 2nd Minsk International Heat and Mass Transfer Forum, May 19-23, 1992, Minsk, Belarus.
8. R. Tao, "Phase transition and structure of electrorheological fluids," The Fluids and Engineering Conference, American Society of Mechanical Engineering, Washington, D. C., June 20-24, 1993.
9. X. Zhang, T. J. Chen, R. N. Zitter, and R. Tao, "Cryogenic Electrorheological Fluids," the Fourth International Conference on ER Fluids, July 20-23, 1993,

Feldkirch, Austria.

10. R. Tao and Qi Jiang, "Simulations of Solid Structure Formation in Electrorheological Fluids," the Fourth International Conference on ER, July 20-23, 1993, Feldkirch, Austria.
11. R. N. Zitter, T. J. Chen, X. Zhang, and R. Tao, "Fluid Flow and Falling Ball Experiments in ER Fluids," the Fourth International Conference on ER Fluids, July 20-23, 1993, Feldkirch, Austria.
12. G. L. Gulley and R. Tao, "Static Shear Stress of Electrorheological Fluids," the Fourth International Conference on ER Fluids, July 20-23, 1993, Feldkirch, Austria.

D. Invited Seminars:

1. R. Tao, "Physics of Electrorheological Fluids," Univ. of Illinois at Urbana-Champaign, Feb. 15, 1991.
2. N. K. Jaggi, "Physics of Electrorheological Fluids," Purdue University, W. Lafayette, IN, Sept 14, 1990
3. N. K. Jaggi, "Physics of Electrorheological Fluids," Southern Illinois University, Carbondale, IL, Sept 28, 1990.
4. N. K. Jaggi, "Physics of Electrorheological Fluids," Clark University, Worcester, MA, Nov 13, 1990.
5. N. K. Jaggi, "Physics of Electrorheological Fluids," Wayne State University, Detroit, MI, Dec 10, 1990.
6. N. K. Jaggi, "Physics of Electrorheological Fluids," University of Michigan, Ann Arbor, MI, Dec 11, 1990
7. N. K. Jaggi, "Physics of Electrorheological Fluids," Harvard University, Cambridge, MA, Jan 9, 1991
8. N. K. Jaggi, "Physics of Electrorheological Fluids," University of Rhode Island, Kingston, RI, Feb 15, 1991
9. N. K. Jaggi, "Physics of Electrorheological Fluids," NRL, Washington, DC, Feb 22, 1991
10. N. K. Jaggi, "Physics of Electrorheological Fluids," NIST, Gaithersburg, MD, Feb 25, 1991
11. N. K. Jaggi, "Physics of Electrorheological Fluids," Illinois Wesleyan University, Bloomington, IL, Mar 7, 1991
12. R. Tao, "Structures and Phase Transition in Electrorheological Fluids", Department of Physics and Department of Material Science, Michigan State University, East Lansing, MI, April 23, 1992.

13. R. Tao, "Electric Field Induced Solidification in a Low Gravity Environment and Electrorheological Fluids", Tampere University of Technology, Finland, May 15, 1992.
14. R. Tao, "The Physical Mechanism of Electrorheological Fluids," Beijing Institute of Technology, Beijing, China, Nov. 25, 1992.
15. R. Tao, "Structure and Phase Transitions of Electrorheological Fluids," Beijing Institute of Technology, Beijing, China, Nov. 26, 1992.
16. R. Tao, "Properties of Electrorheological Fluids," Beijing Institute of Technology, Beijing, China, Nov. 27, 1992.
17. R. Tao, "Materials Technology of Electrorheological Fluids," Beijing Institute of Technology, Beijing, China, Nov. 30, 1992.
18. R. Tao, "Applications of Electrorheological Fluids," Beijing Institute of Technology, Beijing, China, Dec. 1, 1992.
19. R. Tao, "Structure, Phase Transitions, and Applications of Electrorheological Fluids," Institute of Theoretical Physics, Academy of Sciences of China, Beijing, China, Nov. 30, 1992.
20. R. Tao, "Structure, Phase Transitions, and Applications of Electrorheological Fluids," Graduate School of Academy of Sciences and Graduate School of University of Science and Technology of China, Beijing, China, Dec. 3, 1992.
21. R. Tao, "Structure, Phase Transitions, and Applications of Electrorheological Fluids," Anhui Optical Institute, Academy of Sciences of China, Hefei, Anhui, China, Dec. 7, 1992.
22. R. Tao, "Structure, Phase Transitions, and Applications of Electrorheological Fluids," University of Science and Technology of China, Hefei, Anhui, China, Dec. 8, 1992.
23. R. Tao, "Materials Technology and Applications of Electrorheological Fluids," Solid State Institute of Academy of Sciences, Hefei, Anhui, China, Dec. 10, 1992.
24. R. Tao, "Structure and Phase Transitions of Electrorheological Fluids," Department of Physics, Nanjing University, Nanjing, China, Dec. 11, 1992.
25. R. Tao, "The Physical Mechanism of Electrorheological Fluids," Physics Department, Fudan University, Shanghai, China, Dec. 16, 1992.
26. R. Tao, "Materials Technology of Electrorheological Fluids," Physics Department, Fudan University, Shanghai, China, Dec. 18, 1992.
27. R. Tao, "Applications and Prospects of Electrorheological Fluids," Physics Department, Fudan University, Shanghai, China, Dec. 22, 1992.

E. Papers at Professional Society Meetings:

1. R. Tao, "The Structure of the Induced Electro-Rheology Solid", American Physical Society March Meeting, 18-22 March, 1991, Cincinnati, Ohio.
2. X. Zhang, R. N. Zitter, and R. Tao, "Current Modulation by Optical Phonons in p-Type Germanium," abstract in Bull. Amer. Phys. Soc. **36**, 707 (1991).
3. X. Zhang, T. Chen, R. N. Zitter, and R. Tao, "Influence of Electrode Roughness on the Apparent Viscosity of an Electrorheological Fluid", American Physical Society March Meeting, 16-20 March 1992, Indianapolis, Indiana.
4. R. Tao, "Electric Field Induced Solidification in the Gravity-Free Environment," abstract in Bull of Amer. Phys. Soc. **37**, 387 (1992), presented at the APS March Meeting, 16-20 March 1992, Indianapolis, Indiana.
5. G. L. Gulley and R. Tao, "Static Shear Stress of Induced Electrorheological Solids," Abstract in Bull of Amer. Phys. Soc. **37**, 601 (1992), presented at the APS March Meeting, 16-20 March 1992, Indianapolis, Indiana.
6. T. J. Chen, R. N. Zitter, and R. Tao, "Laser Diffraction Study of Crystalline Structure in an Electrorheological Fluid," abstract in Bull of Amer. Phys. Soc. **37**, 601 (1992), presented at the APS March Meeting, 16-20 March 1992, Indianapolis, Indiana.
7. X. Zhang, T. Chen, R. N. Zitter, and R. Tao, "Influence of Electrode Roughness on the Apparent Viscosity of an Electrorheological Fluid," Abstract in Bull of Amer. Phys. Soc. **37**, 602 (1992), presented at the APS March Meeting, 16-20 March 1992, Indianapolis, Indiana.
8. H. Dai and R. Tao, "Analytical Approach to a Model of Deposition on Fibers and Surfaces," American Physical Society March Meeting, 22-26 March, Seattle; Bulletin of the APS, V.38, N.1, 63 (1993).
9. X. Zhang, T. Chen, R. N. Zitter, and R. Tao, "Falling Ball Experiments in Dilute Electrorheological Fluids," American Physical Society March Meeting, 22-26 March, Seattle; Bulletin of the APS, V.38, N.1, 344 (1993).
10. R. Tao, "Apparent Viscosity of Electrorheological Fluids," American Physical Society March Meeting, 22-26 March, Seattle; Bulletin of the APS, V.38, N.1, 344 (1993).

F. Degrees Granted

1. Mr. Gerald L. Gulley, Master of Physics, Southern Illinois University at Carbondale, August 11, 1992.
2. Mr. Hongzhou Dai, Master of Physics, Southern Illinois University at Carbondale, August 11, 1992.

3. Ms. Joanne T. Woestman, Ph. D. in Physics, Northeastern University, Boston, MA, Sept., 1993.

G. Awards, Honors, and Prizes:

1. Rongjia Tao, promotion from Assistant Professor to Associate Professor and tenure, May, 1991, Southern Illinois University at Carbondale, Illinois.
2. Rongjia Tao, promotion from Associate Professor to Full Professor, July, 1993, Southern Illinois University at Carbondale, Illinois.
3. Rongjia Tao, nominated as Honorary Professor of University of Science and Technology of China, June, 1993.